Magnetic Field Modeling With a Set of Electrical Coils

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Introduction

Conventional gradient and shim coils provide one magnetic field term per coil. The sensitive volume of the coils is defined before the coils are designed and has to be chosen sufficiently large to cover all kinds of objects and MR applications.
After the theoretical introduction of the multi-coil (MC) approach for the generation of all 1st- to 4th-order spherical harmonic field terms in the human brain one year ago [1], here we present the first experimental realization of the MC concept in a miniaturized setup [2].

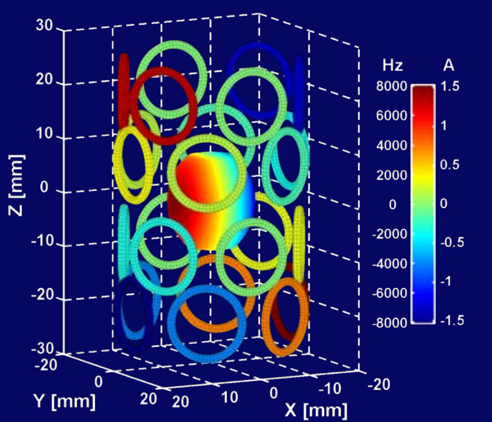

Figure 1: Theoretical coil setup. A total of 24 coils (15 turns, diameter 13 mm) was arranged in 4 rows with 6 coils each on a cylindrical surface (diameter 30 mm). The coils' color coding represents the current distribution to create a 10 kHz/cm X gradient in a centered, barrel-shaped 2.6 mL VOI for which the frequency distribution is coded in color.

We show that gradient and higher order field terms can be generated at high amplitude and high accuracy with a set of localized, individual coils. With the MC approach, the choice of the sensitive volume remains temporally and spatially flexible at all times. Furthermore, the strength and accuracy of the fields are readily traded.

Methods

The MC setup consisted of 24 coils (Ø 13 mm, 15 turns) that were distributed in 4 rings of 6 coils each over a cylindrical surface with an outer diameter of 30 mm. Field simulations and experiments considered a centered, 2.6 mL barrel-shaped volume large enough to cover the head of a mouse as well as single slices of that volume. Figure 1 shows an example current distribution of the MC array (Ampere scale) that generates a 10 kHz/cm X gradient inside the volume-of-interest (Hertz scale). In its experimental realization, coils were made of copper wire and mounted on the surface of an acrylic former. A home-built Bolinger RF coil surrounded the MC setup and was used for RF transmission and signal reception.

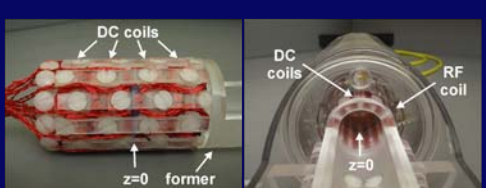

Figure 2: Experimental realization of the MC setup. Left: 24 individual coils were placed on a cylindrical former made of acrylic tube. The inner diameter of the former of 25 mm allowed the placement of a glass bottle or a mouse cradle inside the device. Right: Firm mounting of the former inside the RF resonator provided a close integration of both systems and allowed their simultaneous use.

The inner two rings of coils, i.e. 12 coils, were driven in the ±1 A range; the outer two rings in the ±1.9 A range. Field maps were calculated from seven single-echo GE images (FOV 24 x 24 x 20 mm³, matrix 80 x 80 x 40) that were acquired with the conventional gradient system. To achieve radial MR images of the mouse brain, oblique linear field gradients were generated with the multi-coil setup at 20 kHz/cm (47 mT/m) amplitude and 192 equiangular steps with an 1.4 A maximum current. All experiments were carried out on a 9.4 Tesla animal system. Field simulations, data analysis and hardware handling were done with customized software.

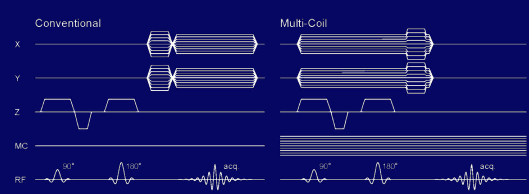

Figure 3: Radial MR imaging with a set of individual coils. Left) A slice-specific spin-echo sequence was extended by a radial projection scheme to allow radial imaging of a mouse head. All gradients of the 'conventional' reference image were generated by the scanners' built-in gradient system. Right) Gradient fields generated with the MC array were used for radial projection readout in a similar MR sequence. The gradients other than the projection readout had to be provided by the scanners' gradient system, since not all of the MC power supplies were switchable at the time. Note, that the MC gradient was permanently on, but was canceled with standard gradients as long as it was not needed.

Results

The established MC approach and setup allowed the reliable generation of high accuracy linear gradient fields.

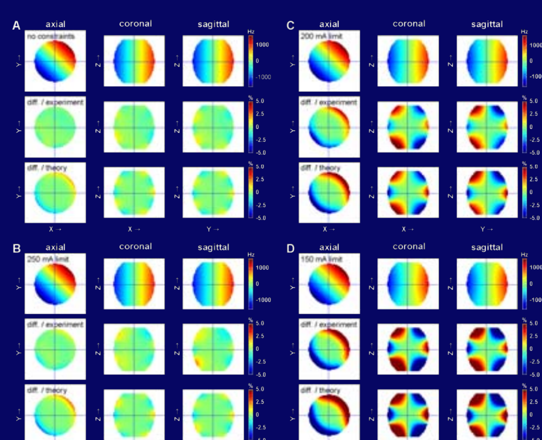

Figure 4: Experimental MC gradient generation of a 2 kHz/cm XY gradient field in a 2.6 mL barrel-shaped volume. (A) An unconstrained MC analysis led to a maximum coil current of 330 mA. The generated field resembled the target field distribution well (1st row, $1\text{-}R^2 = 10^{-4}$ [3]) with an average deviation of 0.5% (2nd row). Experimental results are in excellent agreement with the theoretical predictions (3rd row). (B) A 23% efficiency improvement could be achieved at minimum cost by constraining the maximum coil current to 250 mA. (C) The field accuracy at a further limitation of the maximum coil currents to 200 mA corresponding to a 38% efficiency increase might still be acceptable, while (D) considerable field degradations were observed at a 54% lowered maximum current of 150 mA.

The ability of the MC approach to synthesize more complex field distributions was demonstrated by the generation of second- and third-order spherical harmonic terms.

Results

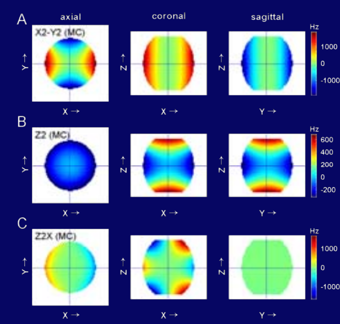

Figure 5: X2-Y2 (A), Z2 (B) and Z2X (C) terms at 1 kHz/cmⁿ amplitude were generated with the MC approach at 980 mA, 434 mA and 783 mA maximum currents, respectively. The experimental field shapes resembled the theoretical target fields with a high degree of similarity ($1\text{-}R^2 \leq 5 \cdot 10^{-3}$) and average deviations of the MC fields were ≤1%.

The limitation of the sensitive volume to single slices allowed efficiency improvements, i.e. the reduction of maximum currents, of factors up to 14 (for the Z2 term) with no accuracy penalty. An additional trade of accuracy for efficiency was always possible and can be used for applications that do not require the highest field accuracy such as phase spoiling or diffusion weighting.

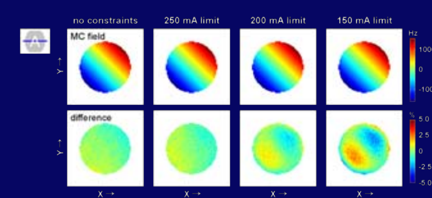

Figure 6: Experimental MC gradient generation of a 2 kHz/cm XY gradient field in a single slice of the barrel-shaped basic volume. Improved field accuracy was achieved for all current constraints when compared to the consideration of the whole barrel-shaped VOI (Fig. 4). For a given accuracy, these improvements directly transferred to strongly reduced maximal currents and improved gradient efficiencies.

Linear gradients generated with the multi-coil approach allowed artifact-free imaging of a mouse head.

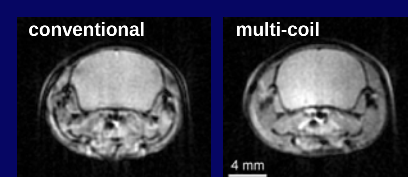

Figure 7: The synthesis of gradient fields at 192 rotation angles with the MC approach enabled radial imaging with the MC sequence described in Fig. 3. The MC image (right) looks identical to the one acquired with a conventional gradient system only (left) and no method-specific artifacts were observed.

Discussion

A multitude of complex field shapes can be generated at high amplitude and high accuracy with a set of localized, individual coils. Lorentz forces, heat and noise generation did not pose any problem due to the applied low currents. Additional efficiency gains and modeling capabilities are expected from an expansion of the coil matrix. The new multi-coil approach provides the framework for the integration of conventional imaging and shim coils into a single multi-coil system and its further development towards a system capable of generating arbitrarily shaped magnetic fields for MR applications in animal and human setups.

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Literature:
[1] C Juchem et al., ISMRM 2009, pp. 3079-3081
[2] C Juchem et al., JMR, *in press* (2010)
[3] C Juchem et al., JMR 183:278-289 (2006)